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General Optical-Limiting Requirements

Mary J. Miller, Andrew G. Mott, and Brian P. Ketchel

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Mary J. Miller, Andrew G. Mott, and Brian P. Ketchel

Sensors and Electron Devices Directorate

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Abstract

Optical-limiting devices and materials may be used to protect U.S. military personnel and equipment from laser radiation damage. Many who consider doing research in this area are not familiar with the U.S. military unclassified requirements for materials or devices that would be fielded. This report attempts to set general guidelines for researchers in the field.

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1. Introduction

The use of lasers in everyday items, such as compact disc players, supermarket barcode readers, and surveyor's equipment, shows how prevalent they are in civilian life. While these applications are generally considered beneficial to society, the current deployment of lasers on the modern battlefield for range finding, guidance, detection, and designation can potentially result in accidental or intentional damage to military optical systems and soldiers' eyes. This increased threat to soldiers' well-being has driven the need for further development of sensor protection devices.

Within the military, three major areas of laser hardening, i.e., sensor protection, are actively being pursued. These areas are officially referred to as level I, level II, and level III, and represent specific effects that a laser has on an optical system. In the scientific community, the three levels are optical augmentation (OA), jamming, and damage, respectively. Optical augmentation is the laser light retroreflection off an optical system that can reveal the system's location to the enemy. Jamming (sometimes referred to as "dazzle") occurs when the optical system is temporarily disabled because of an excessive amount of illumination. Damage is defined as permanent degradation in the performance of an optical system.

The incidence of harmful lasing has been reported in the news media, ranging from the laser light show operator who inadvertently passes his or her laser beams over an aircraft [1] to ships of the former Soviet Union that intentionally tagged military aircraft passing overhead [2]. The development of rugged, compact laser systems has raised concerns that laser countermeasure systems (laser technology designed to damage or disrupt optical systems) could become easily accessible. In addition to the use of sophisticated military countermeasure weapon systems, the potential use of commercial off-the-shelf (COTS) laser systems also as weapons is very real. Virtually anyone with a laser can intentionally disrupt optical systems and damage eyes without understanding the physics of laser systems.

2. Current Status of Fielded Equipment

Sensor protection, defined as anything that can be used to protect optical systems and human eyes from the debilitating effects of lasers, can be achieved by blocking, scattering, diffracting, or absorbing incoming laser light. However, anything that limits incoming light to the sensor or eye will also degrade mission effectiveness to some degree. Therefore, researchers need to devise some type of sensor protection that has the least effect on a soldier's ability to perform the mission without being incapacitated.

Current fielded sensor-protection equipment is limited predominantly to fixed-line filters, shutter systems, or neutral-density filters. Fixed-line filters can be used to selectively eliminate two or three distinct wavelength bands from the incoming light. Unfortunately, with this technology, overall filter transmission is typically between 10 and 20 percent (similar to a pair of sunglasses) and results in a noticeable color distortion. This color distortion can affect many aspects of a mission, from how well a pilot can see his or her gauges to how well a driver can read a map. The low overall transmission and color distortion inherent to these filter devices reduce their effectiveness in the field, especially for dusk and dawn deployment.

Mechanical or electro-optical (EO) shutters can provide protection to an optical system, but there are some serious limitations to their effectiveness. Shutter technology has improved to the point that an EO shutter can respond within 10 µs [3]. While that might be fast enough to prevent damage to a system facing a continuous wave (CW) laser threat, it is too slow when encountering a short-pulsed laser threat. The first pulse (or first few) enter the system unhindered since this first pulse must be detected to activate the protective shutter. In both the CW and pulsed cases, however, the optical system is effectively jammed once the shutter is in place.

Neutral-density filters have also been used to provide limited protection to optical systems. These devices reduce the total amount of light entering the system. Unfortunately, this technique results in degradation of performance because of lack of contrast and an overall transmission value that is too low. For some systems, this amount of transmission loss is acceptable or can be compensated for, given the alternatives of jamming or permanent damage.

In summary, the current methods that counter today's laser threats are extremely limited in their overall performance. Future threats to our military systems include lasers that can rapidly change their operating wavelength from the predicted wavelengths that are easily protected by fixed-line filters. This capability is called "frequency agility," which means that the laser can vary its output wavelength to other nonprotected wavelength lines or bands and defeat an optical system [4]. Future counter-countermeasure (CCM) systems must provide protection across the entire operational bandwidth of the sensor. The approaches to sensor

protection used today, e.g., shutters, fixed-line filters, etc, cannot protect against these future laser systems. Over the last decade, many concepts have been examined and are in various stages of research and development. Passive devices (those activated by the incoming radiation itself) are found to be the best approach to counter the frequency-agile, short-pulse threat. In general, the ability of a material or device to reduce the transmission of incoming laser light is known as optical limiting.

3. Requirements

Any sensor protection device or material, whether designed to retrofit existing equipment, or to integrate into new sensor system, must have minimal effect on the performance of the sensor. We discuss in the following paragraphs some of the key requirements for any sensor protection device.

One of the most important requirements for sensor protection is that the device be effective over the entire operating wavelength band of the sensor system being protected. This operation is typically referred to as "broadband" and refers to the device in both the linear state and the operational state. There are four major operating wavelength bands that correlate to fielded optical systems: the visible (VIS) band, which covers the 400- to 700-nm operating spectrum of the human eye; the near infrared (NIR) band, which covers the 600- to 900-nm operating spectrum of typical night-vision devices; and the mid-infrared (MIR) and far-infrared (FIR) bands, which cover the 3- to 5-μm region and 8- to 12-μm region, respectively, of the spectra common in IR sensor systems. As a rule, any sensor protection device must have a high transmission in the "off" state and low transmission in the "on" state across the entire band. While it is impractical to quote an exact "minimally acceptable" transmission, a common rule of thumb can be applied. For protection devices in the VIS band, the transmission should be no lower than 40 percent. For the NIR to FIR regions, an 85 to 90 percent transmission is a practical range to approach. Although the above transmission values are reasonable goals, exceptions can be (and are) made to these requirements. The end user is more concerned about the reduction in system performance than about the overall system transmission. An example of a technology that defies this general rule would be a tristimulus filter, or "tristims." Tristims are composed of three spike filters that transmit only certain spectral lines in the blue, red, and green spectrum. These filters essentially provide a statistical approach to protection. The overall transmission of these combined spike filters is much lower than the requisite 40 percent for eyewear; however, because the lines chosen can be placed judiciously within the eye's spectral response, the effective transmission will seem much higher to the user.

For the VIS region, where the primary sensor is the human eye, the maximum permissible exposure (MPE) [5] is considered the maximum safe level of total intraocular energy (TIE) that should be allowed into the eye. This value is 0.2 μJ for pulses less than 17 μs and equates to a fluence level of 0.5 $\mu J/cm^2$ for the dark-adapted eye. For low-input energies, this goal is not hard to reach, but as higher energies are incident on an optical system, the MPE becomes harder to achieve. A more realistic achievement would be a factor of 5 to 10 times higher than MPE. For the other sensors, the maximum allowable energy levels are determined by the damage threshold of the most sensitive system components, which are usually the detector elements. Because of security issues, these numbers cannot be quoted in this report. In all cases, the protection device must start

working at or before the maximum allowable energy levels for that system and stay "on" until the device fails. We define the working range of the device as the dynamic range. The dynamic range is the ratio of the input energy at which the device fails to the input energy at which it begins to protect. The ratio of transmitted energy to maximum incident energy in orders of magnitude protection is referred to as optical density (OD):

$$OD_{system} = -\log_{10} (E_T/E_{max.\ inc.}) \,, \tag{1}$$

where E_T = transmitted energy and $E_{max.\ inc}$ = maximum incident energy before device failure. In general, for systems involving the human eye, an OD of 4 is considered the desirable minimum protection. Therefore, the dynamic range must also be at least 4 orders of magnitude, which means that before the system fails, it must protect against the first 4 orders of magnitude of dangerous energy levels. In some cases, system failure is caused by damage to the sensor protection device, which sometimes limits even more energy from entering the sensor. This should not necessarily be considered as part of the working dynamic range, since from the point of damage on up in input energy, the sensor protection device has become a "sacrificial" system (will need replacing).

One requirement that researchers often overlook is the temporal bandwidth of the sensor protection device. While a 10-ns pulse is commonly thought of as the most likely threat on the modern battlefield, there may be laser systems available in the near future with a wide range of pulsewidths. Whether a dangerous laser pulse is delivered within a short pulse (<40 ns), a long pulse (40 ns to 1 ms), or CW exposure (>1 ms), it must be countered. At the very least, a proposed protection device must consider one of the previous bands as a target goal.

Additional design requirements that must be considered are the environmental stability of the material or device and its toxicity. As with any military device, exposure to temperature extremes would range from the freezing temperatures of the Arctic (–65 °F) to the searing temperatures of the desert (160 °F). Enclosing the material in an environmentally resistant container or cell can solve some of these problems, but not all. Even if enclosed, a toxic material or material mixed with a toxic solvent would have a much lower chance of being fielded than a material that posed no threat to the environment or the end user.

In most cases, the degree to which the above mentioned requirements are addressed is determined by the material (or materials) used in the design of the optical-limiting device. Once the limitations of the materials are overcome, the optical system issues can then be addressed.

A sensor protection device is generally designed as an insert, an add-on, or a replacement to a specific optical system. In all cases the field of view of the military optical system must not be greatly reduced. If the sensor protection device is an insert to a preexisting system and needs to be located at the focal plane of that system, then the device must be tested using focusing optics that simulate the "f-number" (f/#) of the system. In

almost all Army systems, f/#s range from f/5, as in the M1 gunner's auxiliary sight, to f/1.2, as in the PVS-5A night-vision goggle. A sensor protection device is generally required to work well under low f/# conditions.

The size, weight, and complexity of the device design also affect the user's acceptance of a potential optical-limiting device. Sensor protection devices that need multibeam configurations or long preprocessing stages to be effective are not practical unless those optics are designed in a very small, light package that preserves the original optical specifications of the target optical system. Few military systems are originally designed with extra room near a focal plane to easily accommodate some of the most promising designs. Sensor protection concepts that will be used by the foot soldier must also be designed with weight and electrical requirements in mind. Few man-portable optical systems are designed such that they can easily be modified without increasing their weight. Although pilots and soldiers are trained to fight and perform missions with night-vision gear strapped to their heads, this is far from comfortable. The additional weight on the front of the helmet can become a distraction after a period of time and reduce a soldier's effectiveness.

Finally, another important requirement that must be considered when designing an optical-limiting system is optical scatter. In many of today's sensor protection concepts, nonlinear scattering and nonlinear refraction are often considered as potential mechanisms for optical limiting. In general, both of these nonlinear mechanisms rely on system apertures to block forward-propagating laser light that is directed out of the linear optical path. Unfortunately, most of the scattered light stays in the optical system and can seriously degrade the contrast. This light, in effect, becomes a source of jamming to the very system that it was designed to protect. While jamming is less detrimental than damage, it can still degrade mission effectiveness.

4. Current Research

Much of the recent work done for the military has acknowledged the limitations that we have found through extensive nonlinear optical (NLO) materials work. To date, no single material has been found that can provide the required protection levels for any of the optical systems. At one time, sensor protection was just a matter of finding a good NLO material—now it is an engineering issue as well.

The first engineering concepts proposed to improve limiting used optics to help activate the sensor protection devices that are placed in a system. One of the earlier concepts proposed was a tandem limiter approach (fig. 1), which was designed to increase the damage threshold and ultimately the dynamic range of protective devices [6,7]. The tandem concept relied on a chain reaction in which the element at focus would limit the incoming energy up to a level just before its damage point. At this level of energy, the limiter element directly preceding it would switch on and protect the element at focus.

Another concept that uses engineering to compensate for, or overcome, the limitations of the nonlinear material is a natural extension of the tandem approach called the gradient limiter [8,9] (see fig. 2). This concept is based on the variation in absorption of the nonlinear medium. The idea is to design the device so that the highest concentration of an excited-state absorbing material is located at the focus. The concentration of the sample decreases as the distance from the focus increases. This variation of the absorbing material results in two distinct advantages over a solid material of the same thickness. The first advantage is that the overall transmission loss for the devices is reduced. By decreasing the absorption (i.e., increasing the transmission) systematically throughout the material, the amount of laser intensity that reaches focus is increased and this results in a faster initiation threshold. The second advantage is that the focus when positioned near the back of the sample is within a highly nonlinear medium, which could provide protection for the optical system. As the input energy increases, the region of material preceding the focus (with a lower absorption) would receive enough intensity to initiate a nonlinear response. This process continues to work its way back along the input beam providing protection for the remaining region of material.

Scientists today are actively pursuing techniques that would allow many nonlinear materials to be collocated so that each material may help defeat a different temporal pulse or waveband, improve overall transmission, or even increase the dynamic range [10]. Each material would fill a specific niche, but the overall device could protect over a much wider range of threats than the individual materials could protect. Mixing materials in "cocktails," and embedding them in sol-gels, glasses, plastics, and other matrices are just a few examples of this approach (see fig. 3). Unique photonic bandgap devices [11,12] and fiber bundles filled with nonlinear materials [13,14] are all being designed so that they overcome the shortcomings of state-of-the-art materials.

Figure 1. Tandem limiter.

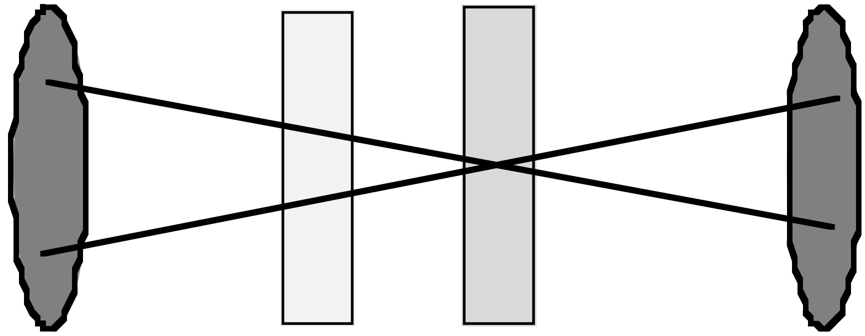


Figure 2. Gradient limiter.

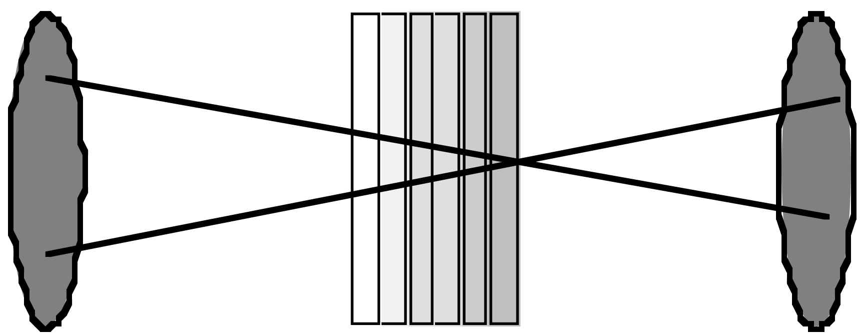
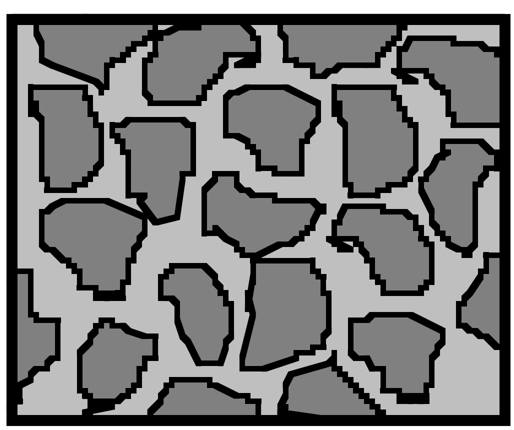


Figure 3. Nonlinear material embedded within a sol-gel host.



Besides devices being engineered, materials are being molecularly tailored to fulfill the military's stringent requirements more effectively. Two-photon absorption materials are being developed with very large coefficients [15,16], and bichromophores are being designed with large nonlinear cross sections and much broader operating bandwidths [17]. The same is true of excited-state absorption dyes: work is being performed to increase their bandwidth, increase the excited-to-ground-state cross-section ratio, move the excited-state wavelength band, and even improve their solubility in nontoxic solvents [18–20].

The latest ideas in sensor protection go further today to meet some or most of the aforementioned requirements than they did just a few years ago. Although many unique and creative optical limiter designs have been proposed and even built and tested, the best solution has yet to be found.

5. Practical Suggestions for Researchers in the Field of Optical Limiting

Many practical suggestions exist for researchers to keep in mind while investigating optical limiting for the protection of military sensors, including human eyes. Anticipating which potential optical system a material or device will be used to protect can let the researcher factor the system requirements into the protection device design from the onset of the project.

One of the biggest problems facing government scientists is interpreting the optical-limiting capabilities of materials based on the varied conditions under which researchers obtain their data. Optical limiting, especially in materials that exhibit large nonlinear refractive or scattering components, often looks promising in high f-number systems. However, high f-number systems are not the norm in military optical systems. Therefore, to truly demonstrate potential optical-limiting capability, one should test a material or device under more stringent, low f-number conditions.

Almost all nonlinear effects cause severe phase distortions on the transmitted laser beam that can seriously limit the optical sensor's capability to focus effectively to a sharp point. Analysis of this effect through measurements such as the encircled energy technique can contribute more information about the limiting capabilities of a material or device than optical-limiting experiments by themselves.

Researching materials with large nonlinearities over a narrow bandwidth is important; however, it is imperative to consider how these materials can be altered or combined in some way to provide a broader functional wavelength response. Researchers should also try to test material optical-limiting capabilities in various pulsewidth regions. A material or device that performs well across large temporal bands will be a much more effective countermeasure, and thus a less costly solution than multiple fixes to counter multiple threats.

6. Conclusions

The use of lasers in the military combined with the abundance of optical systems has created an environment where sensors need to be protected or they could sustain optical damage, thus reducing their military effectiveness. The use of nonlinear materials, mechanisms, and devices will ultimately reduce the threat of frequency-agile laser weapons. Many researchers have worked in this field for years and are aware of the stringent requirements needed to provide truly effective sensor-protection devices. Unfortunately, many other researchers, especially newcomers to the field, are not. While the study of nonlinear materials and mechanisms in academia is perfectly valid, the practical application of these materials and devices can only be successful if the requirements of the end users are well known to the working community.

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U.S. Army Research Laboratory
Attn: AMSRL- SE-EO email: amott@arl.mil
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